AN INVESTIGATION OF CHIP FORMATION WITH TOOLS OF FINITE EDGE RADIUS

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CERTIFICATE

This is to certify that the work on "AN INVESTIGATION OF CHIP FORMATION WITH TOOLS OF FINITE EDGE RADIUS" has been carried out under my supervision and has not been submitted elsewhere for a degree.

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B.K. MISRA

CONTENTS

NOMENCLATURE

α	Rake angle of the tool
α^*	Critical rake-angle of the tool
a_{min}	Minimum chip-thickness
C_1	Chip tool contact length
δ	Included angle
F_{Hp}	Total ploughing force per unit width of workpiece in the direction of tool motion
F_{HC}	Total cutting force per unit width of workpiece in the direction of tool motion
F_{cp}	Ploughing force tangential to the tool base per unit width of workpiece
F_H	Total force in cutting direction
F_N	Force normal to the shear-plane
F_S	Force along the shear plane
F_{tp}	The ploughing force normal to the tool base per unit width of workpiece
F_V	Total force in vertical direction
L	Resultant force acting on the wear land of the tool
μ	Coefficient of friction
N	Force along the tool-rake face
N_B, N_D	Force normal to the cutting edge at points B and D respectively
P	Pressure acting normal to the tool-edge
P	Resultant force acting on rounded portion of the tool-rake face

P'	Resultant force causing the ploughing of the metal (Albrecht)
P_N, P_N'	Forces normal to the tool edge (L'VOV)
P_{τ}, P_{τ}'	Frictional forces tangential to the tool edge
Q	Resultant force acting on the linear portion of rake face of the tool
R	Resultant force in cutting-direction (Gurin)
R'	Resultant force in vertical direction (Gurin)
r	Radius of the cylindrical edge
R_x	Force in cutting direction at a particular point on the tool-edge
R_y	Force in vertical direction at a particular point on the tool-edge
t	Uncut chip thickness
t_c	Thickness of the chip
$t(\theta^*)$	Depth of neutral point
θ	Angle of contact at any depth of cut
θ^*	Neutral-point angle
	Yield shear stress of the material of workpiece
V_1	Non-dimensional velocity indicated in Godograph (Fig. 9b)
V_2	Non-dimensional velocity of material around the lower surface of the cutting edge (Fig. 9b)

ABSTRACT

In orthogonal machining, cutting is carried out by a wedge shape tool with rake and clearance faces joined by a rounded cutting edge which may be approximated by a section of a cylinder. The geometry of the tool largely determines the chip formation process, power requirement, life and wear of the cutting tool and quality of machining. The purpose of this work is to investigate the effect of rounded tool edge. The main objective was to define the neutral point on the cutting edge where transition from ploughing to cutting occurs. A theoretical analysis which equates the forces in the direction of tool motion on a blunt, and a sharp tool with a finite wear land predicts that this neutral point angle is 37.5° which corresponds to an effective rake angle of - 52.5°. Good agreement with experimental result is obtained. A new criteria for 'machinability' is also discussed in terms of rake angle where transition from ploughing to cutting occurs.

CHAPTER-I

INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION:

Most theories of metal cutting assume that the tool is infinitely sharp. This simplified approach has been used to predict the shear plane angle. Merchant (1) has analysed the metal cutting process for a sharp edge tool and proposed the force diagram (Fig. 1) for a positive rake tool.

A similar force diagram can be drawn for tool of negative rake angle. These forces cause the shearing of the work material, producing new work surface. Though the theory based on the sharp edge tool clarifies to a great extent the mechanics of the metal cutting process, yet some unexplained factors remain.

To name a few such instances, one may note that the coefficient of friction on the chip-tool interface has usually been found to be rather high compared with the values found by direct experiments on surfaces having contaminating films. Further, this coefficient of friction, as given by the theory, has a peculiar property, that is, it varies with the tool geometry. The chip-tool coefficient of friction increases with increasing rake angle of the tool (2).

Albrecht (3) has pointed out that the natural sharpness of a tool after grinding rake and clearance faces corresponds to a edge radius of about 0.0003 inch (0.00762 mm).

Often tool sharpness in metal cutting is associated with tool wear. Thus if the flank or crater wear of a cutting tool is in an advanced stage the tool is often described as blunt or dull. So we define the sharpness of an orthogonal tool as a function of the radius of the tiny cylindrical surface connecting flank and rake face surfaces. This small cylindrical surface is developed on the cutting edge during the grinding process of the tool. The way in which it happens is shown in Fig. (2). As the grinding wheel works along the tool face or tool flank, the tiny particles of tool material will break off at the extreme edge where the edge is so thin that the material can not stand the impact of grinding wheel grains. This leads to a rounded surface as shown in Fig. (2a). The cross-section of this rounding would be a curve which can be very well approximated by a segment of a circle as shown in Fig. (2b). The radius, r, of such a circle gives the magnitude of the rounding and thus can be adopted as a measure of the sharpness of the tool. The magnitude of radius characterizing the tool sharpness depends on a number of factors such as tool material, method of grinding, and some others, like included angle, S .

Albrecht (3) has shown that the radius, $r = a \tan^{n}(S/2)$, where a and n are parameters which determine the position of the curve in the

vertical direction in Fig. (3). These parameters also include the effects of all other variables which affect the sharpness radius apart from the included angle, S.

Other factors which will contribute to this rounding of tool edge are built-up edge formation near the tool edge (5) and the development of cracks which separate the discontinuous chips from its segments.

1.1 PREVIOUS WORK:

The modified force diagram of orthogonal cutting process with rounded edge tool was suggested by Albrecht (3) as shown in Fig. (4). L is the force acting on the wear land of the tool flank. The force P' causes the ploughing of the metal, adjacent to the wear land, into the workpiece. At point 2 the actual separation of the metal from the workpiece occurs. The friction directions on either side of this point oppose each other. The different directions for the friction force results in a discontinuity of the force polygon at point 2. At points 1 and 3 discontinuity can occur if the coefficient of friction on the rake face and on the wear land differs from that on the rounded edge. If the coefficient of friction can be considered as constant along the whole tool surface over which metal slides, the portions of the force polygon from 0 to 2 and from 2 to 4 will be without discontinuities.

The assessment of the tool face force Q has allowed the determination of a real value of the coefficient of friction on the tool face and it was found (3) that this friction coefficient value does not vary

with the variation in the rake angle. In this way the old paradox of varying of the coefficient of friction on the tool face with rake angle can be explained.

It may appear that the character of the flow near the tool edge, with or without a build-up-edge is only of theoretical interest. It is, however, important from practical point of view since surface finish and accuracy of machining depends on the metal flow characteristics in this region.

It has been established that the size of the build-up depends on the cutting speed and the rake angle of the tool. This aspect has been discussed in detail by Heginbotham et.al. (4). The built-up-edge is commonly conceived as an "active" dead metal zone in that it grows in size, becomes unstable, and then fractures. But, a small stable dead metal zone of constant size has invariably been thought to exist in certain circumstances when machining materials which do not exhibit large, active formations. Fig. (5) shows this type of built-up-edge formation.

Assuming that the flow is possible around the tip of a round edge tool without the formation of a built-up-edge, then incompressibility condition will suggest that all material above the cut surface (the base of the tool) should be removed in the form of chip, and all material below the cut surface should remain as part of work. However, this later material may rise well above the level of the cut surface as it passes through the plastic zone, and the line which separates chip and work

material would probably be some thing like AB in Fig. (6). The point A may be termed as 'Neutral Point' on the surface of the tool. Plastic material on either side of A will move away from A, and the friction stresses applied by the tool to the plastic material in the neighbourhood of A will be directed towards A.

The metal particles above the line AB, are deformed by the rake face and are formed into a chip, whilst the particles below this line are deformed by the clearance face and are not detached from the body of the metal. Thus the chip formation process is performed by the rake face, whilst the surface layer of the machined component is formed by both the rake and clearance faces.

The angle θ describes the position of the neutral point. A few investigators (8,9) have defined this neutral point on the edge of the tool in metal cutting, but without any valid proof. Gurin (8) gives a diagram of the forces within the zone of deformation when cutting with diamond tools, establishing that the stability of the cutting process diminishes with the decrease in the chip thickness, the access of the new layers of metal into the chip formation zone become more difficult and, at a specific ratio of the undeformed chip thickness to the cutting edge radius, cutting becomes impossible. From Fig. (7), the ratio of the vertical and horizontal components of the pressure R of the metal being removed on the tool varies along the rounded cutting edge. In this case the separating point A is the point in which horizontal R_x and

vertical R_y components are equal. This implies that the force ratio R_x/R_y is unity at this point which is not justified. This point will be discussed later.

N.P. L'VOV (9) described the neutral point, by applying the theory of pressure working of metals stating that, to admit the metal through the roll, the force of the rolls on the metal should (in a critical case) be perpendicular to the direction of rolling. His force model is shown in Fig. (8). He suggested that the particles bordering with point A, from underneath the resultant $\bar{R} = \bar{P}_\tau + \bar{P}_N$ should be horizontal. This is possible only when $\theta = \pi/4$, because $\bar{P}_N = \bar{P}'_N$, $\bar{P}_\tau = \bar{P}'_\tau$, consequently, $\bar{R} = \bar{R}'$. This proposition applies to the point A itself, where the force $P_\tau = P'_\tau = 0$, and horizontal and vertical resultants are equal. Thus the minimum chip thickness, a_{min}, was

$$a_{min} = r\ (1 - \cos\theta) = 0.293\ r \qquad (1)$$

since $\theta = \pi/4$.

During actual cutting, however, the stresses are such that plastic deformations, wear and even chipping of the tool-edge occurs, thereby altering the radius r and the cutting wedge geometry. For these reasons, the value of a_{min} , will be greater than the theoretically obtained values.

1.2 PRESENT WORK

It has already been established (10) that the shape of an abrasive grain on the grinding wheel can be approximated by a sphere.

The analysis of the cutting action of a spherical grain is complex because of the fact that the forces act in a three-dimensional space. However, if the force model is analysed in a two-dimensional space then some aspects of grinding can be explained very easily. In a two-dimensional-space, the centre section of a sphere as well as the cylinder (if viewed from the end) form a circle, therefore, the analysis to some extent will be applicable to both the cases.

In the present work it is proposed to present a theoretical analysis of orthogonal machining with tools of finite edge radius. In actual practice the edge radius is generally around 0.0003 inch (0.00762mm). However, to simplify the analysis and experimental verification, the edge radius will be exaggrated. Tools of edge radii upto 0.060 inch (1.524 mm) will be used. The main objective will be to establish the depth of cut or the effective rake angle where the chip formation begins. This critical depth of cut is of considerably importance during finish machining at fine depths of cut.

CHAPTER-II

THEORETICAL ANALYSIS

To locate the neutral point on the cylindrical edge of the tool, a theoretical model is proposed based on the following assumptions:

1. The metal is assumed to be an isotropic, rigid-perfectly plastic and non-strain hardening, and obeys the Von-Mises Yield Criterion and associated flow rule. Hence the material is incompressible and elastic strains are negligible.

2. 'Plastic-recovery' of the material is negligible.

3. The edge of the tool is approximated by the section of a cylinder.

4. The coefficient of friction around the cylindrical surface (edge radius) is constant.

5. Continuous chips are formed when the depth of cut is above the neutral point.

The analysis presentad here is based on the concept that the force in the direction of tool motion during cutting with a sharp tool having finite wear land, and with a blunt tool should be equal at the neutral point. In metal cutting practice when t is less than $t(\theta^*)$ where t is the uncut chip thickness and $t(\theta^*)$ is the depth of the neutral point, there will be ploughing only while for the case where t

is greater than $t(\theta^*)$, both ploughing and cutting will be there. The problem is therefore considered in two parts.

The first part will comprise the force analysis on a blunt tool and in the second part, the force analysis is performed on a sharp tool with finite wear land and rake angle varying from 0° to -90°. For simplicity, we will designate the force in the direction of tool motion during cutting with sharp tool as 'cutting-force' and with blunt tool as 'ploughing-force. At t equal to $t(\theta^*)$, the cutting-force should be equal to the ploughing-force. The effective rake angle may be obtained by drawing a tangent at the tool face as shown in Figs. 8 and 10. This rake angle will be $(\frac{\pi}{2} - \theta^*)$, where θ^* is the angle of neutral point. It is clear that effective rake angle will decrease (less negative value) as t is increased.

The ploughing force (F_{Hp}) acting on the rounded portion of the tool, can be determined from an upper-bound solution. Johnson (11) assumed the existance of circular cylinderical upper-bound surface in the plastic regions beneath cylindrical rollers and forming tools. It is reasonable to assume that a similar plastic region will exist beneath the lower curved surface of a rounded edge when cutting, in the absence of an active build-up formation. This is shown in Fig. (9a). The hodograph for the best upper-bound is shown in Fig. (9b). It is clear from Fig. (9a) that the total ploughing force tangential to the tool base per unit workpiece width is equal to the sum of the ploughing

force associated with the shearing at the tool base within the ploughing region ABC and ploughing force per unit width associated with the velocity discontinuity AEC. Thus the total ploughing force tangential to the tool base per unit width of workpiece (F_{Cp}) will be equal to

$$F_{Cp} = \tau (ABC)\, V_2 + \tau (AEC)\, V_1$$

where τ is the material yield shear stress at the tool base, V_2 is the nondimensional velocity of material around the lower surface of the cutting edge, V_1 is the nondimensional velocity indicated in hodograph and (ABC), (AEC) are the arc lengths as shown in Fig. (9a).

Substituting the values,

$$F_{Cp} = \frac{\tau\, r\, \theta}{\cos\theta/2} + \pi \tau\, r\, \sin\theta/2\, \tan\theta/2$$

The component of F_{Cp} in the direction of tool movement will be

$$F_{Hp_1} = \tau\, r \left[\frac{\theta}{\cos\theta/2} + \pi \sin\theta/2\, \tan\theta/2\right]\left[\cos\theta/2\right] \qquad (2)$$

The ploughing force normal to the tool base (F_{tp}) due to the material bearing on the boundary ABC (for a Von Mises material in which the normal stress is equal to $\sqrt{3}\,\tau$) will be given by the expression

$$F_{tp} = 2\sqrt{3}\,\tau\, r\, \sin\theta/2$$

The component of F_{tp} in the direction of tool movement can be written as

$$F_{Hp_2} = 2\sqrt{3}\,\tau\, r\, \sin\theta/2 \quad \sin\theta/2 \qquad \ldots\ldots\ldots \qquad (3)$$

From equations (2) and (3) the total ploughing force F_{Hp} in the direction

of tool movement is expressed as

$$F_{Hp} = F_{Hp_1} + F_{Hp_2} \qquad \ldots\ldots\ldots \qquad (4)$$

Defining, $F_1(\theta) = F_{Hp}/\tau\ r$, equation (4) gives,

$$F_1(\theta) = \left[\theta + 6.6 \sin^2\theta/2\right] \qquad \ldots\ldots\ldots \qquad (5)$$

The force analysis for the sharp-edge tool with finite wear land under the same cutting conditions that is, same depth of cut, cutting speed, width of cut, friction etc. As mentioned earlier, the effective rake angle of a blunt tool can be expressed as the angle between the vertical axis (OC') and the tangent, AC (drawn on the cylindrical surface at a point which corresponds to the uncut chip thickness, t) as shown in Fig. 10a. When the depth of cut is increased the negative rake angle decreases. The effective rake angle of a blunt tool may be considered the same as rake angle of a sharp tool.

In the case of sharp-edge tool, the cutting force (F_{HC}) will be calculated assuming the sticking friction condition over the chip tool contact area. When machining with tools of positive rake angle it has been shown (18)that both sticking and sliding friction conditions exist on the rake face. However, the region of sliding friction is generally small compared to the region over which stricking friction exist. In metal cutting practice the value of chip-tool contact length generally varies from 2 to 3 times the depth of cut. However, with tools of large negative rake angle this contact length is likely to be much higher.

Experimental results of Komanduri (15) indicate that the chip-tool contact length (C_1) on the rake face is approximately size times the length of rake face corresponding to the depth of cut (t), that is, $C_1 \simeq 6\ t/\cos\alpha$. These experiments were conducted with tools of rake angles varying from 0° to -55°. The above value of the chip-tool contact length will be assumed in present analysis for sharp tool.

The forces acting on the sharp-edge tool are shown in Fig. 10a. τ is the material yield shear stress and 'p' is the normal pressure acting on the tool rake face. For simplicity, a linear distribution of 'p' over the chip-tool contact length as shown in Fig. 10a will be assumed. In actual practice this distribution is generally hyperbolic (18). The value of pressure 'p' can be calculated from the slip-line field. The proposed extreme alpha-slip line DC is shown in Fig. (10a). It is assumed here that all the alpha-slip lines, in the region ADC, are similar to the slip line DC.

The pressure p, acting on the tool face in the absence of an active build-up may be estimated as follows, using the Hencky equation (assuming a constant value of τ)

$$p + 2\tau\ \phi_1 = \text{constant along an alpha-line} \qquad (6)$$

where ϕ_1 is the anticlockwise rotation of the slip line from an arbitrary datum.

The major principal stress acting in the direction parallel to the surface at the uncut surface is compressive and if the datum

direction is chosen to be the free uncut surface then the constant in the Hencky equation (6) may be shown to be equal to $-\tau$. Therefore,

$$p + 2\tau\phi_1 = -\tau \qquad \ldots\ldots \qquad \ldots\ldots\ldots \qquad (7)$$

The workpiece surface ADE is a free surface, therefore, the slip line DC will meet it at 45 degrees. Due to the assumed sticking friction on tool face, the slip line DC will meet the tool face at 90 degree. The anti-clockwise rotation of DC can be shown to be equal to $(45° + \alpha)$. Substituting this value of ϕ_1 in equation (7), the value of 'p' can be written as,

$$p = -\left[2.57 + 2\alpha\right]\tau \qquad \ldots\ldots\ldots\ldots \qquad (8)$$

The total cutting force (F_{HC}) acting on the tool rake face per unit width of the workpiece is given as

$$F_{HC} = (AC)\left[3p\cos\alpha - 6\tau\sin\alpha + \tau\right] \qquad (9)$$

where AC can be found from the geometry of Fig. 10. This is equal to $r(1-\sin\alpha)/\cos\alpha$. Substituting this value of AC and 'p' from equation (8) in equation (9),

$$F_{HC} = \frac{\tau r\,(1 - \sin\alpha)}{\cos\alpha}\left[3\,(2.57 + 2\alpha)\cos\alpha - 6\sin\alpha + 1\right]$$

Defining, $F_2(\alpha) = F_{HC}/\tau r$, gives the following equation

$$F_2(\alpha) = \frac{(1 - \sin\alpha)}{\cos\alpha}\left[3\,(2.57 + 2\alpha)\cos\alpha - 6\sin\alpha + 1\right] \qquad \ldots \qquad (10)$$

when, $t = t(\theta^*)$

$$\alpha = (\pi/2 - \theta^*)$$

the,

$$F_1(\theta) = F_1(\theta^*), \quad F_2(\alpha) = F_2(\pi/2 - \theta^*)$$

In these equations the terms in brackets indicate functions.
Using equation (5),

$$F_1(\theta^*) = \left[\theta^* + 6.6 \sin^2\theta^*/2\right] \quad \ldots\ldots \qquad (11)$$

and from equation (10),

$$F_2(\pi/2 - \theta^*) = \left[\frac{1 - \cos\theta^*}{\sin\theta^*}\right] \left[3(5.71 - 2\theta^*) \sin\theta^* - 6 \cos\theta^* + 1\right] \quad \ldots\ldots \qquad (12)$$

equating equations (11) and (12), that is,

$$F_1(\theta^*) = F_2\,(\pi/2 - \theta^*) \quad \ldots\ldots\ldots\ldots\ldots \qquad (13)$$

Equation (13) will give the solution for θ^* , the neutral point angle, Graphical solution, Fig. 14, gives θ^* to be equal to 37.5°. This gives an effective rake angle of −52.5° where chip formation begins. This means that the cutting conditions exist when θ^* is greater than 37.5°, below which ploughing occurs. Therefore, the equation (11) is valid only for θ^* is less than 37.5° and equation (12) applies for θ^* is greater than 37.5°.

CHAPTER-III

EXPERIMENTAL DETAILS:

The experiments consist of two phases of work. During the first phase the force measuring device (dynamometer) was calibrated and in the second phase the neutral point was observed.

The tools of radii ranging from 0.025" to 0.060" in steps of 0.005" were used on three widely different work-materials, mild steel, aluminium and lead. The details of tools and workpiece test piece, are given in appendix (I). Force measurement was carried out by using a milling dynamometer shown in Fig. (12) and the output was recorded on an Encardio-rite pen recorder. The complete experimental setup is shown in Fig. (11).

3.1 CALIBRATION OF MILLING-DYNAMOMETER:

For conducting the calibration, the dynamometer was rigidly mounted on the table of an HMT horizontal Milling Machine. A prooving ring of 500 lbs. capacity was placed vertically, directly above the dynamometer for calibrating the vertical axis and horizontally for calibrating the cutting-axis. In both cases the output from the two bridges were recorded. The output from both the bridges was used to check the cross sensitivity in either direction. The readings were taken during both loading and unloading of the dynamometer.

The cross sensitivity in the cutting direction was found to be negligible (less than 0.5%) while the cross sensitivity in vertical direction was some what significant. This simplified the problem since the correction was needed only in one direction. This was done by plotting several graphs, shown in Fig. (15, 16). It was found that the cross-reading of horizontal force in vertical direction helped the vertical force. So, to get the actual vertical force, the cross-reading of horizontal force was subtracted from the recorded value of the vertical force. It is useful to note here that the hysteretic effect in higher range of loading is significant.

The gain, amplification and sensitivity positions on the pen recorder were recorded; these positions will be kept the same throughout the experiments.

3.2 OBSERVATION OF NEUTRAL POINT ON THE TOOL-EDGE:

For locating the neutral point on the tool-edge, the orthogonal cutting with tools of large edge-radii was performed on an HMT horizontal Milling Machine at low table speed (240 mm/min). Several vertical lines were scratched on the testpiece at 3 mm intervals as shown in Fig. (13), in order to measure the depth of cut at a particular point. The specimen was then mounted on the dynamometer and a finish cut by a sharp tool was taken to ensure the flat top surface. The length L and distances D_1, D_2 ... etc. of specimen (Fig. 13) at all vertical lines were measured using a precision micrometer (least count 0.01 mm). The testpiece was

finally mounted on the Milling dynamometer at a slight angle so that an increasing depth of cut was presented to the tool. The slope of the specimen over the length L was measured using a dial-gauge (least-count, 0.002 mm).

The tool and specimen were set such that the tool-edge would make contact with the workpiece after it has travelled a few milimeter distance. The automatic feed was applied to the table and the tool-chip contact zone was observed continuously through a microscope of 10X magnification. The onset of chip formation was marked on the recorder using the Event-Marker and the table motion was also stopped at the same time. The tool and specimen were disengaged carefully and the testpiece was then taken out.

The distances D_1 , D_2,...... etc. were again measured using the precision micrometer. The differences between these and original D will give the depth of cut taken at different point. The depth of cut at which the chip appeared will express the neutral point angle θ^*. The depth of cut could also be determined from the recorder-graph since the cutting-speed, recorder paper speed and the slope of the testpiece were known.

Several cuts with a sharp tool were taken to remove the work-hardened material before any new experiment was performed. The whole process was then repeated with tools of various edge radii and other workpiece materials. The forces were also recorded for different depth of cut with a tool of 0.025" edge-radius.

CHAPTER-IV

RESULTS AND DISCUSSION

Experimental results obtained were plotted to get the different characteristics of chip formation with finite edge tools. Fig. (17) shows the variation of vertical and horizontal forces (F_V and F_H) with depth of cut for a particular tool - workpiece combination. In this case the work material was lead. The curves of F_V and F_H intersect at a depth of cut which corresponds to 97° angle of arc of contact. Theoretically ~~th~~ this angle should be 90°. This small difference between the experimental and theoretical values is well within the experimental-error.

Fig. (18) shows the plot of neutral-point angle (and effective rake angle) versus edge radius of the tool for different work-materials. Fig. (19) represents the plot of the depth of cut where the chip is formed t (θ*) versus edge radius. These curves show only a small variation with change in edge radii. The values of the neutral point angle are in the range of 28° to 33°. The proposed theory, however, gives this value to be equal to 37.5°. It is believed that the discrepancy in the theoretical and experimental values is due to the elastic and plastic recovery of the work material and frictional condition at the tool-edge which were not taken into consideration while formulating the theory. Abdelmoniem

et. al. (13) found that the 'plastic - recovery' may be of the order of 10 to 20% of the uncut chip-thickness (t) while cutting with a sharp-edge tool of large negative rake angle. The elastic-recovery will be very small and the effect of this is negligible on the final-readings due to the following reasons.

The tool edge is elastically deformed due to the pressure acting on it thereby changing the sharpness-radius to a higher value which may be defined as the 'effective-edge-radius'. This effective-edge-radius will primarily depend on the hardness of the tool and workpiece material and the cutting temperature. Higher the workpiece-hardness, higher will be the effective-edge-radius. But on the other hand, harder the workpiece material higher will be the elastic-recovery. Large edge-radius will cause an increase in the depth of cut for extreme no-chip condition. So, in the final measurement of the depth of cut, the elastic-flattening of the edge of tool and elastic-recovery of the workpiece material will oppose each other. The correction can, however, be made by introducing a factor relating the elastic deformations of tool-edge and workpiece. In case of soft metals such as aluminium, lead and zinc neither of these two are likely to be of any significance.

The friction conditions between the tool and workpiece will also affect the value of effective rake angle. The value of friction in ploughing and the cutting will be different because in the former case the actual friction will be very near to the sticking friction value due to the

pure ploughing, while in the later case the actual friction will be other than the sticking one. The friction value along the edge will also vary. The trend of its variation is not known.

In chapter - 1 it was discussed that according to L'VOV (9) the effective rake angle should be 45 degrees. The theory proposed by him compared the cutting process with rolling of strips. This can be subjected to the criticism, since in rolling there are several factors which do not compromise with cutting conditions. These can be described as follows.

Firstly, rolling and cutting with tool of finite edge radius will have different friction values due to the different type of contact between the tool and workpiece. In case of rolling the rollers roll on the workpiece while in cutting the tool slides over the workpiece. So, the friction values in these two cases are likely to be different.

Secondly, the rolling process is symmetrical along the longitudinal axis while cutting process will be unsymmetrical if the rolling concept is applied.

The forces (F_V and F_H) measured for different edge radius tools and workpiece materials (Aluminium and Lead) were plotted against the edge-radius. These curves show the increasing value of the forces with increase in edge radius Fig. (22). The trend of the force variation is non-linear, however, theoretically it should be linear because the forces are directly proportional to the edge-radius as represented by equation (5). It is believed that this non-linearity in the curve is due to the

non-linear volume of metal displaced by the cylindrical-edge of the tool with increasing edge radius. Consequently, the side flow of metal will also show an increasing non-linear trend with increase in edge radius. So that, different widths of cut are presented to the tools in cutting. The cutting and thrust force in orthogonal machining vary with width of cut (1) that is, an increase in the width of cut increases the force values in both directions. Therefore, the non-linearity in the curves are justified.

Fig. (23) shows the plot of force ratio (F_H/F_V) versus the cutting edge radius for aluminium and lead. The trend of the curves for both the metals are same. However, the value of ratio (F_H/F_V) is different for these metals. The increasing trend of the curves is due to the side flow of the materials as discussed earlier. The difference in the values of the ratio (F_H/F_V) for aluminium and lead can be due to the different friction values and material-characteristics which are a function of strain-hardening. According to Gurin (8), this force ratio should be unity at the point of chip formation. But the present investigation shows that this is not true.

A tool of natural sharpness has the edge-roundness of approximately 0.0003 inch. However, after a few initial cuts with a freshly-ground tool, the edge radius will become large due to wear. In such a case, the proposed analysis will be of a great use. For a tool of certain edge-radius, the minimum depth of cut (where the chip is formed) can be

calculated. If the depth of cut is below the critical depth then no chip will be formed and only the ploughing will occur. In finish machining the depth of cut is usually very small so, a tool of substantial edge-radius will give poor surface finish.

Knowing the wear rate of tool-edge, the cutting time for which the tool had been in operation, the minimum depth of cut can be suggested for a typical tool in order to get good surface finish.

The minimum rake angle of a sharp tool that will produce chips can also be obtained using the cutting model shown in Fig. (10b). It is clear from Fig. (10b) that the chip material exists in the domain bounded by the shear plane and the rake face. This suggests that as the rake face becomes more and more negative, the shear angle (ϕ) will become smaller and smaller but, one would imagine, the rake face AC would 'catch up' on the shear plane BC until finally, the two planes will coincide. At this point there is no material with which to form a chip so that pure-ploughing will be observed.

With this as a basis, an attempt was made to obtain the informations from metal cutting literature regarding probable values of the rake angle at which pure-ploughing might be expected to occur. In metal cutting operations, such as turning, rake less than -10° are very rarely used so that any information will necessitate extrapolation over a very large range. When this was done by plotting the angle between shear plane and rake plane (ψ) against the rake angle (α) Fig. (20) for data

obtained from turning tests (20) on SAE 1020 steel cut in the presence of an emulsion type coolant, the value of rake angle at which $\psi = 0$ is of the order of $-56°$.

Some investigators (13, 14, 15) have performed the experiments to find the no chip condition with sharp-edge tool. Rubenstein, et. al. (14) found that the no chip condition with two different materials (aluminium and copper) lies between rake angles of $-50°$ and $-55°$. Komanduri (15) also performed the experiments with negative-rake tools. He plotted a graph of thrust force and cutting force as a function of negative rake angle at a particular depth of cut, Fig. (21). The non-linearity of the curves start at a rake angle of about $-55°$. It is believed that this non-linearity in the curves indicate the beginning of ploughing range. In the cutting range, that is, when the metal is removed in the form of continuous chip, the force variation with the rake angle is generally linear (16).

4.1 A NEW APPROACH TO MACHINABILITY:

The machinability of metal is governed by several factors. According to Shaw (17) the term machinability is more frequently used in connection with the discussion of one or more of the 'inputs', although it is best measured in terms of one of the 'outputs'. Under normal circumstances the best criterion for rating machinability in terms of work-material, chemistry, heat treatment, tool material, cutting fluid, cutting-speed, tool-angles, or other input, is machining cost per part.

Under special conditions where machine capacity is limited and production output is of major concern, the proper machinability criterion is the number of parts per unit time. Several investigators have discussed Machinability in terms of above factors. It is proposed here that the critical rake angle of a sharp tool where chip formation begins would be a worthy consideration as a criterion of workpiece machinability.

It has been discussed earlier that as the negative rake-angle of a tool increases the rake face comes nearer to the shear plane and at a certain rake-angle, both the rake-face and shear plane coincide. At this situation, no chip is formed and all the material is ploughed. This condition will result in a very poor machinability. From the metal cutting data it is known that, at a given rake angle and given cutting conditions, ductile materials give a higher shear plane angle than the brittle ones (1). Thus it might be expected that with a ductile workpiece material the rake plane will catch up with the shear plane faster than a brittle workpiece material. Therefore the critical rake angle will be smaller (more negative) for ductile materials in comparison with those of brittle ones. Therefore, it can be said that the brittle materials are machinable still at higher value of effective rake angle.

A similar argument can also be applied for grindability of work materials. The spherical shape of an abrasive grain on the grinding wheel results in a force analysis similar to that of orthogonal machining in a two-dimensional space.

A grinding wheel consists of an aggregation of abrasive grains which are bonded together. These grains are graded so as to lie within a limited size range but will include a variety of shapes. Moreover their orientation are random so that during grinding, a workpiece is presented with a variety of rake angles. If the workpiece properties and in particular its degree of ductility are such that the limiting rake angle is fairly high (small negative value) then only a proportion of the grains which meet the workpiece will remove the material in the form of chips, the remainder of grains will only cause ploughing, that is, displace the metal to the sides and the process will be inefficient. On the other hand if the limiting rake angle is low (large negative value) then a much greater proportion of grains will cut and the process will be correspondingly more efficient. Further ploughing is likely to cause an increase in the attritions wear of grinding wheel, hence rapid loading and lower tool life. Loading of grinding wheel will be fast in case of very ductile materials due to the excessive side flow caused by ploughing. Therefore, a grinding wheel which gives poor grindability for materials of high ductility, will give the better grindability for materials of low ductility.

CONCLUSIONS:

It has been established that a critical depth of cut exists during machining with tools of finite edge radius which signifies the onset of chip formation. Below this depth of cut no cutting is possible and the material is merely pushed to the sides. The theoretical model predicts the rake angle corresponding to this depth of cut to be -52.5°. The value compares well with the experimental results. Further, this critical effective rake angle does not appear to vary with tool-edge-radius.

The critical rake angle appears to vary with material-properties and the approach can be used as a criterion for 'Machinability'.

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APPENDIX-I

TABLE (1) (Refer to Fig. 13)

Specimen's Material	L (cms)	0 (cms)	W (mms)
AL	4	2.5	3.24
Pb	4	2.5	5.1
MS	4	2.5	4.69

TABLE (2)

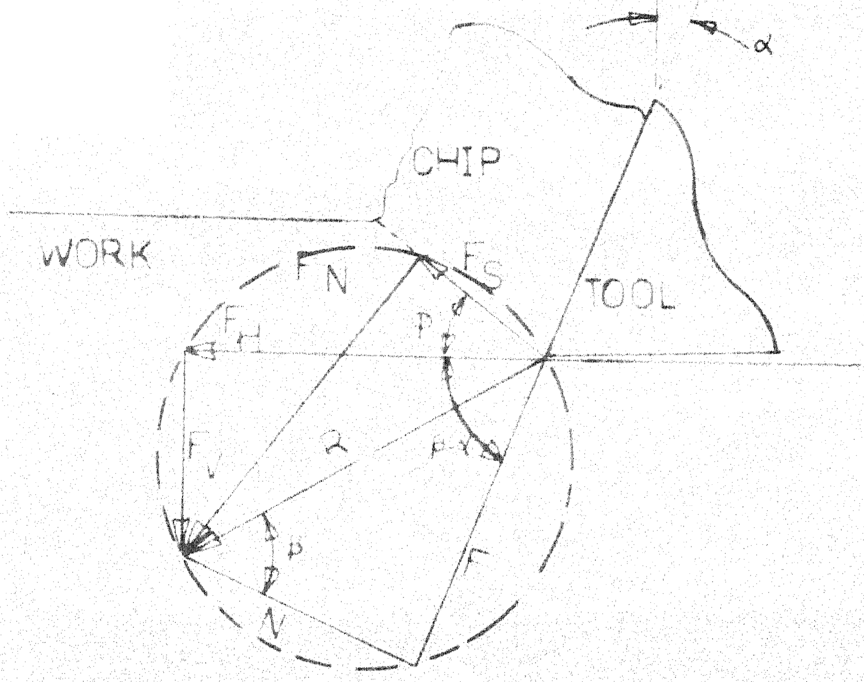
TOOL MATERIAL = 10% COBALT STEEL

RAKE ANGLE = 30°

CLEARANCE ANGLE = 9°

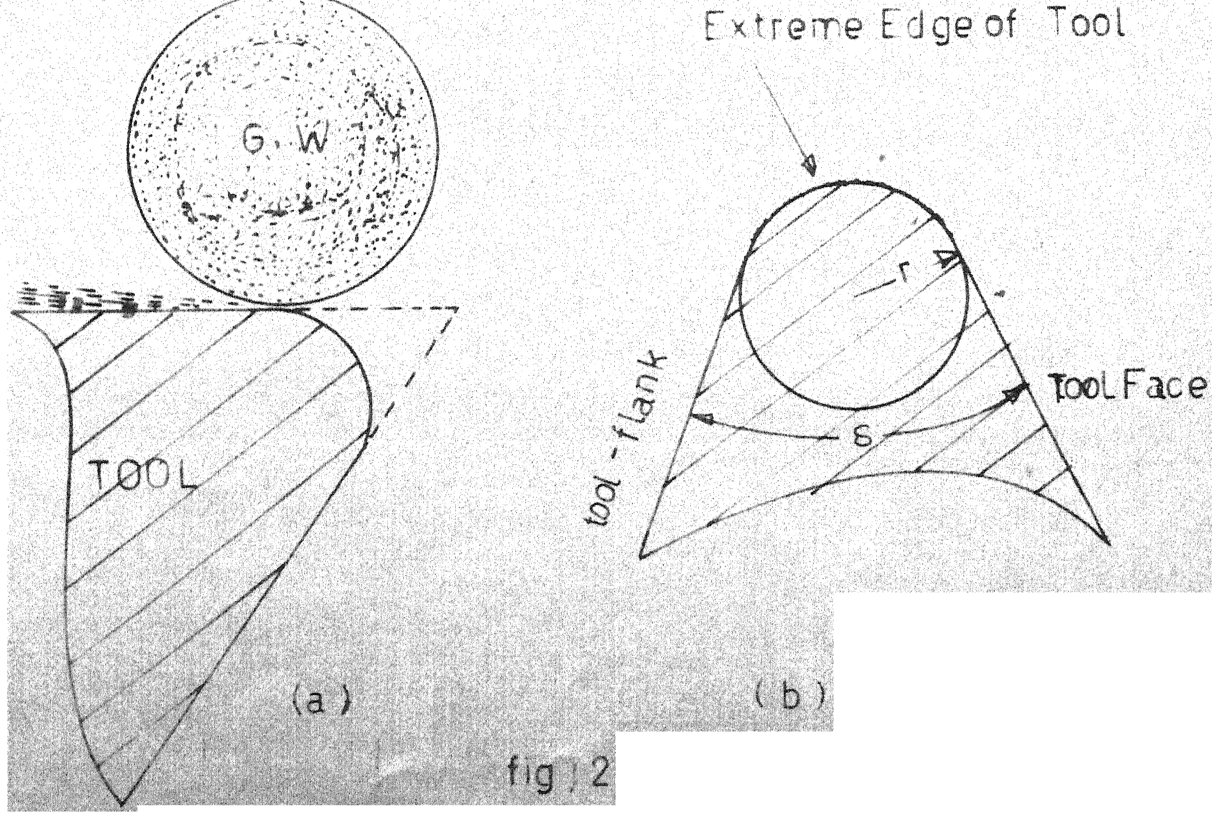
EDGE RADIUS (r) -

.025"	.040"	.055"
.030"	.045"	.060"
.035"	.050"	



CHIP
WORK
TOOL

fig 1



G.W
TOOL
(a)
Extreme Edge of Tool
tool-flank
Tool Face
(b)

fig 2

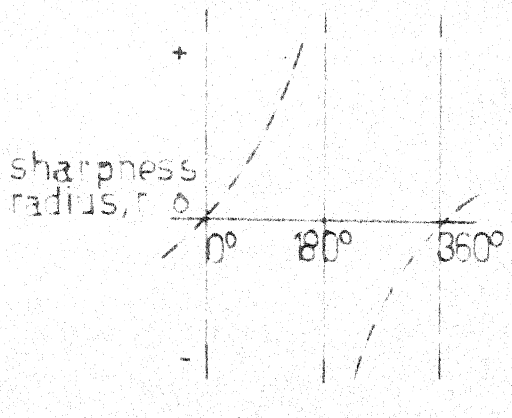


fig 3

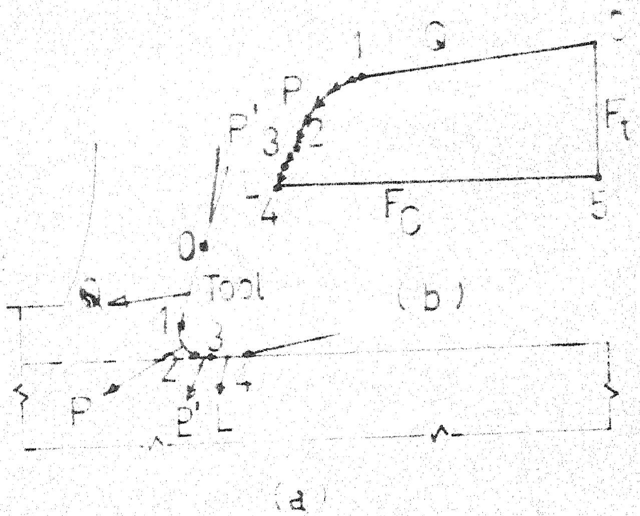


fig 4

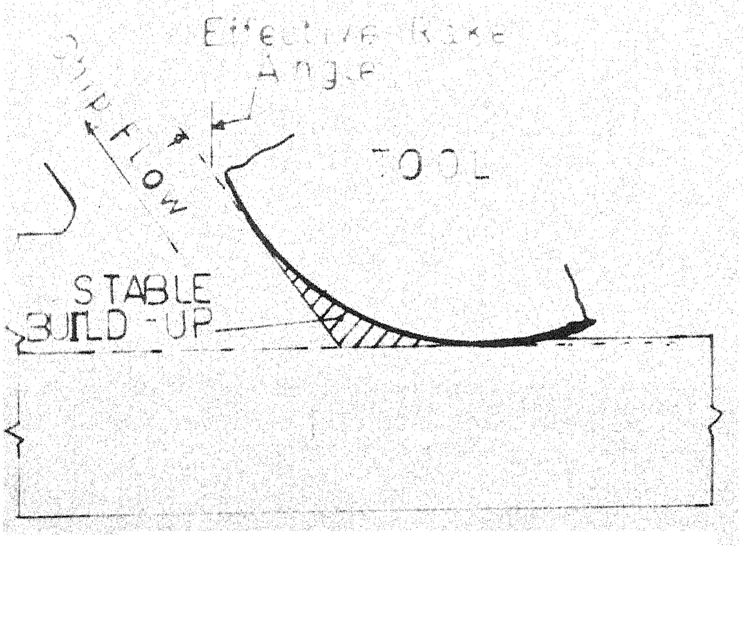
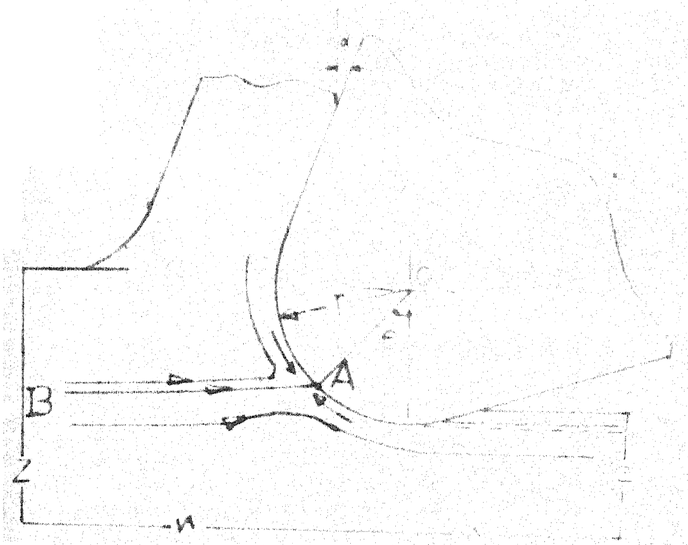


fig: 5



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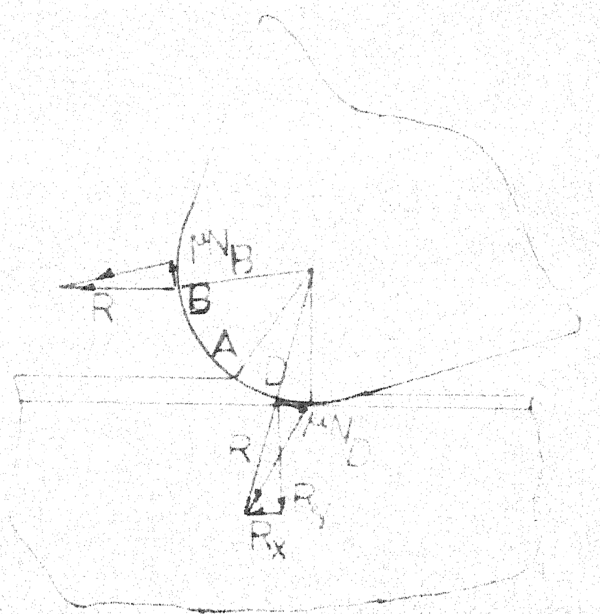

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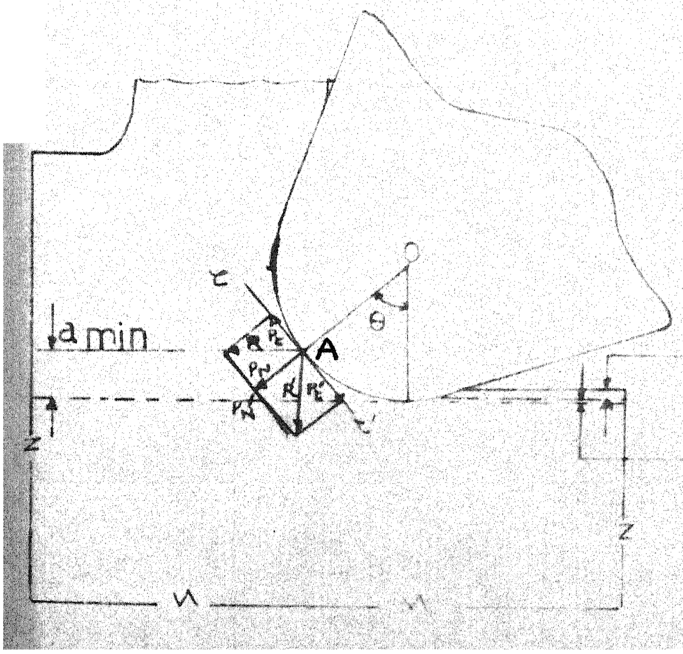

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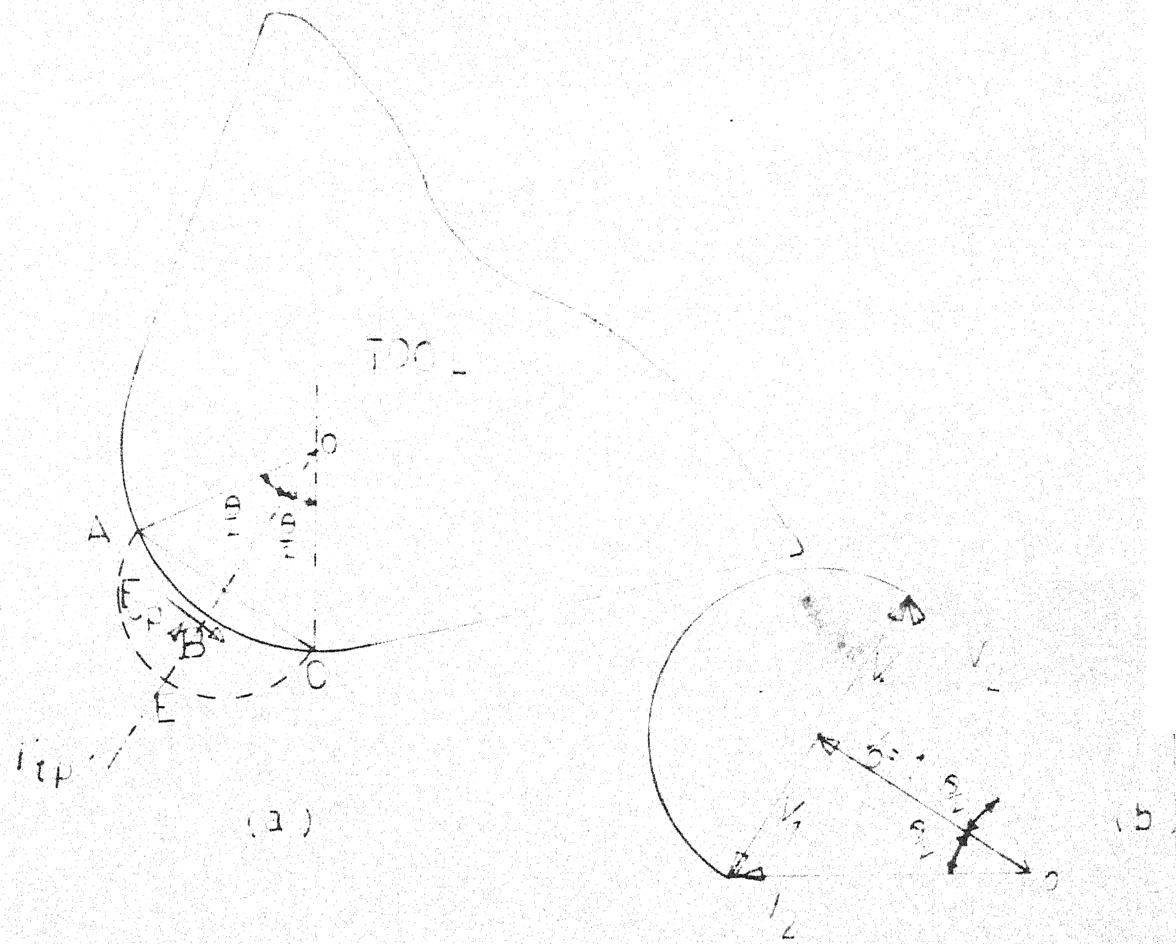

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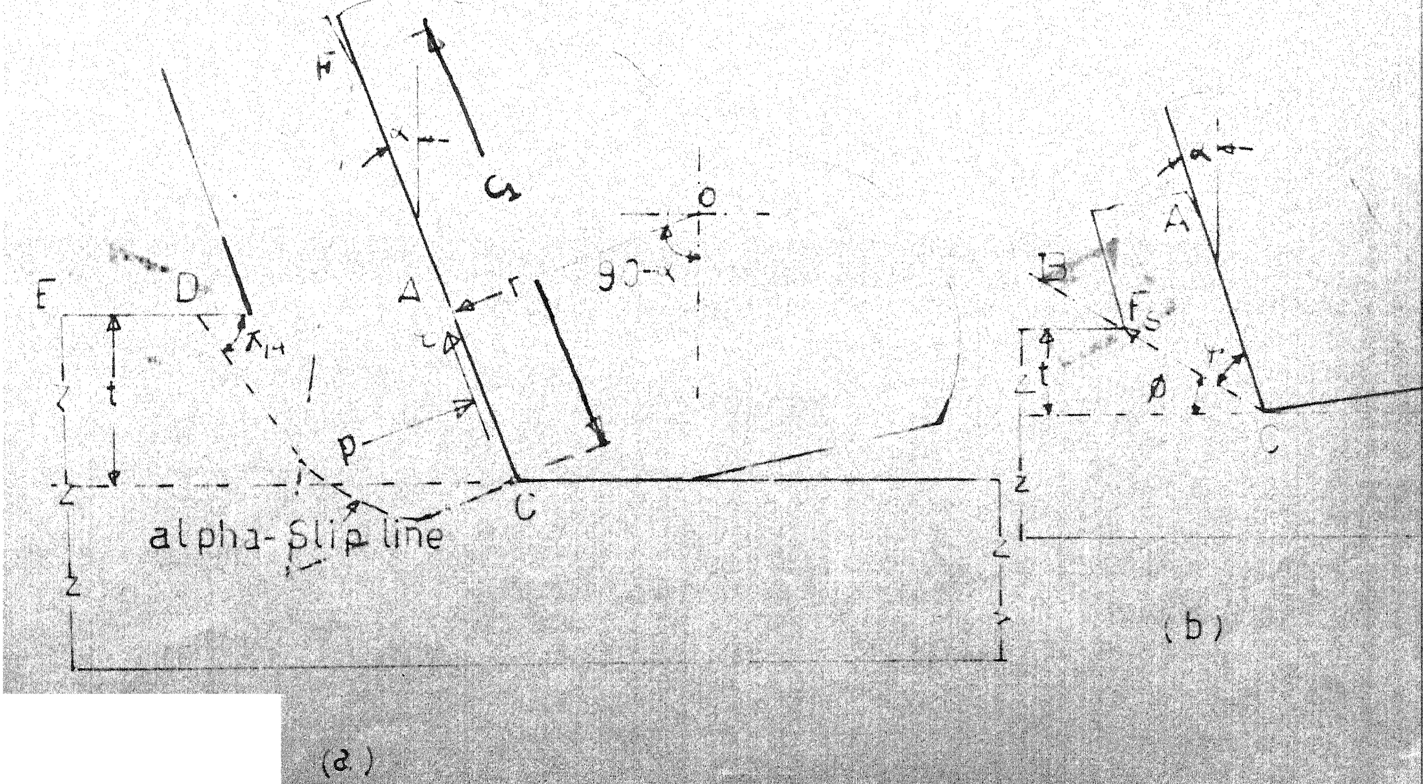

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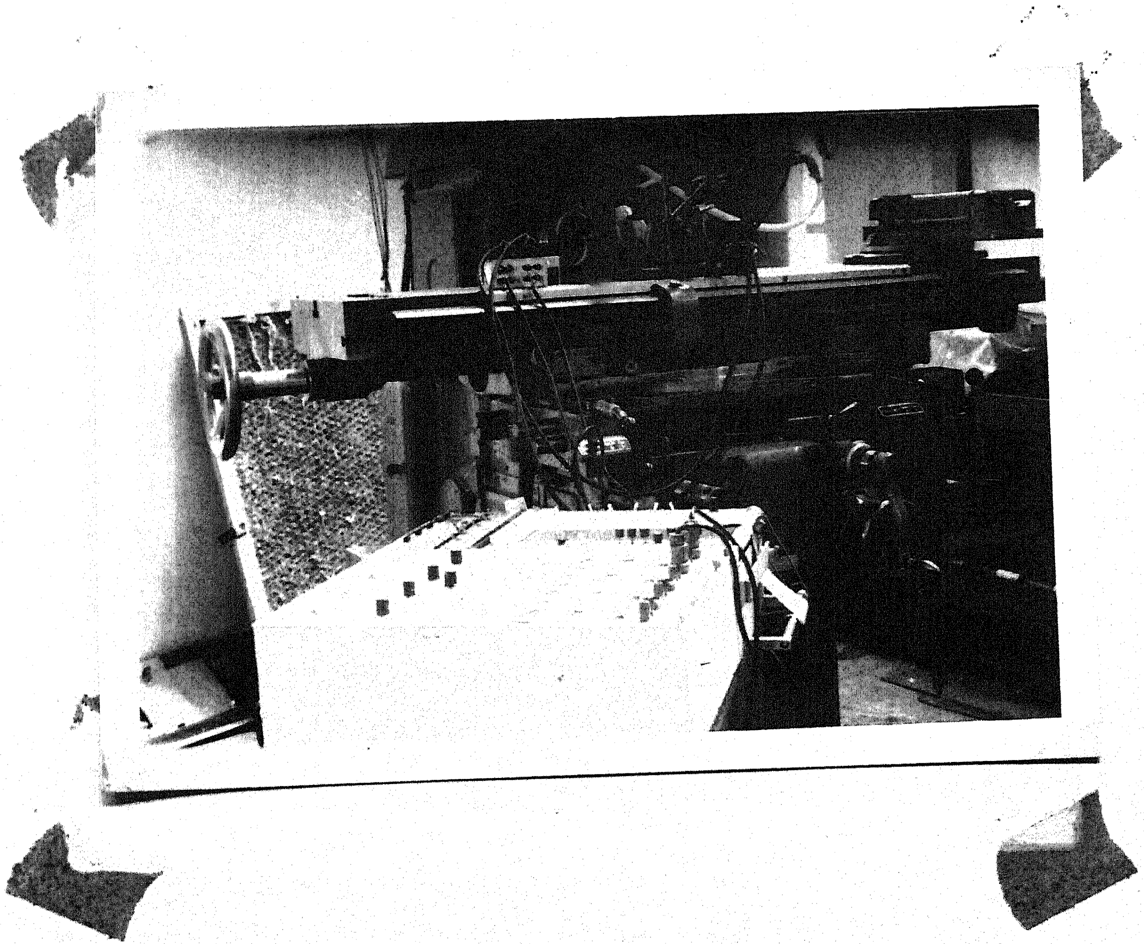


fig: 11

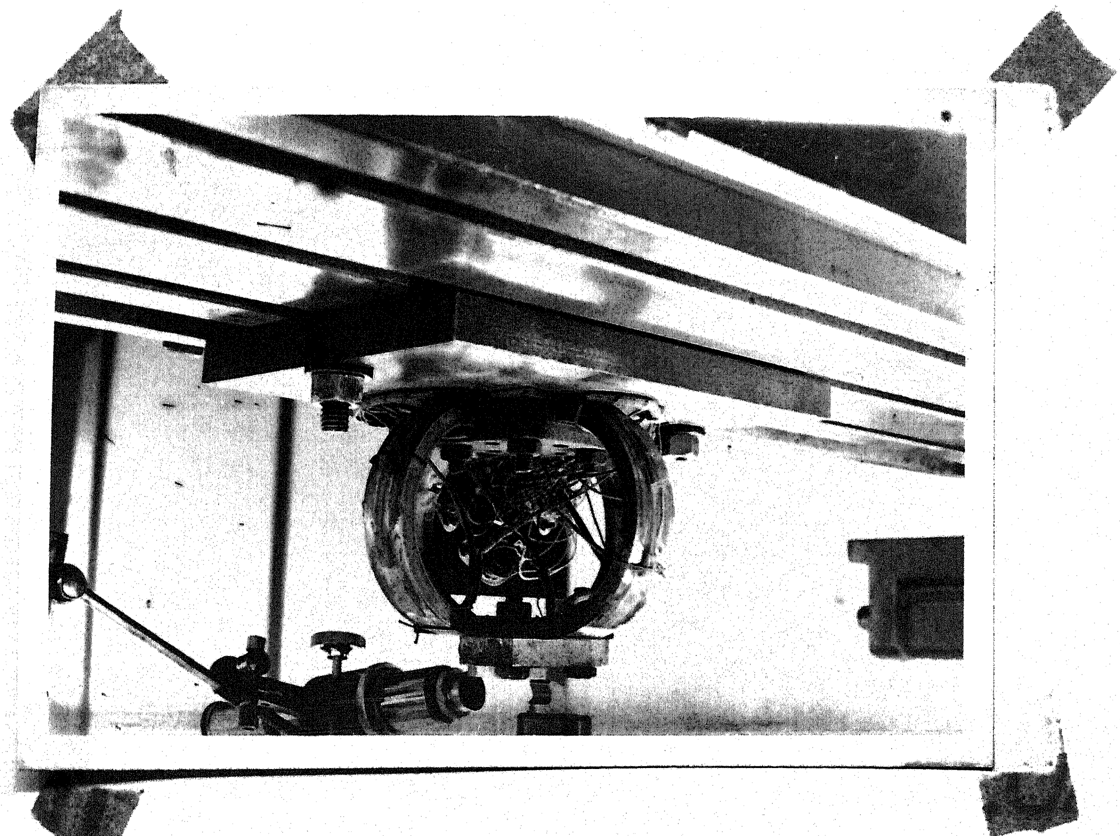


fig: 12

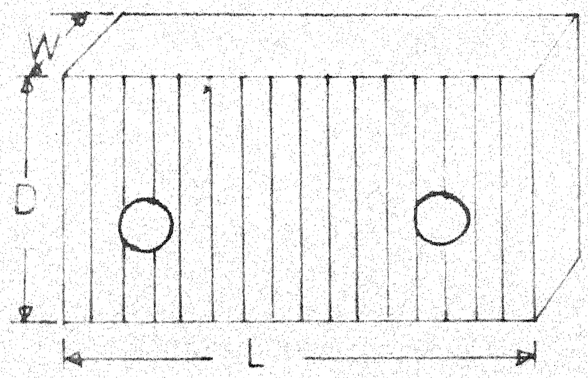


fig: 13

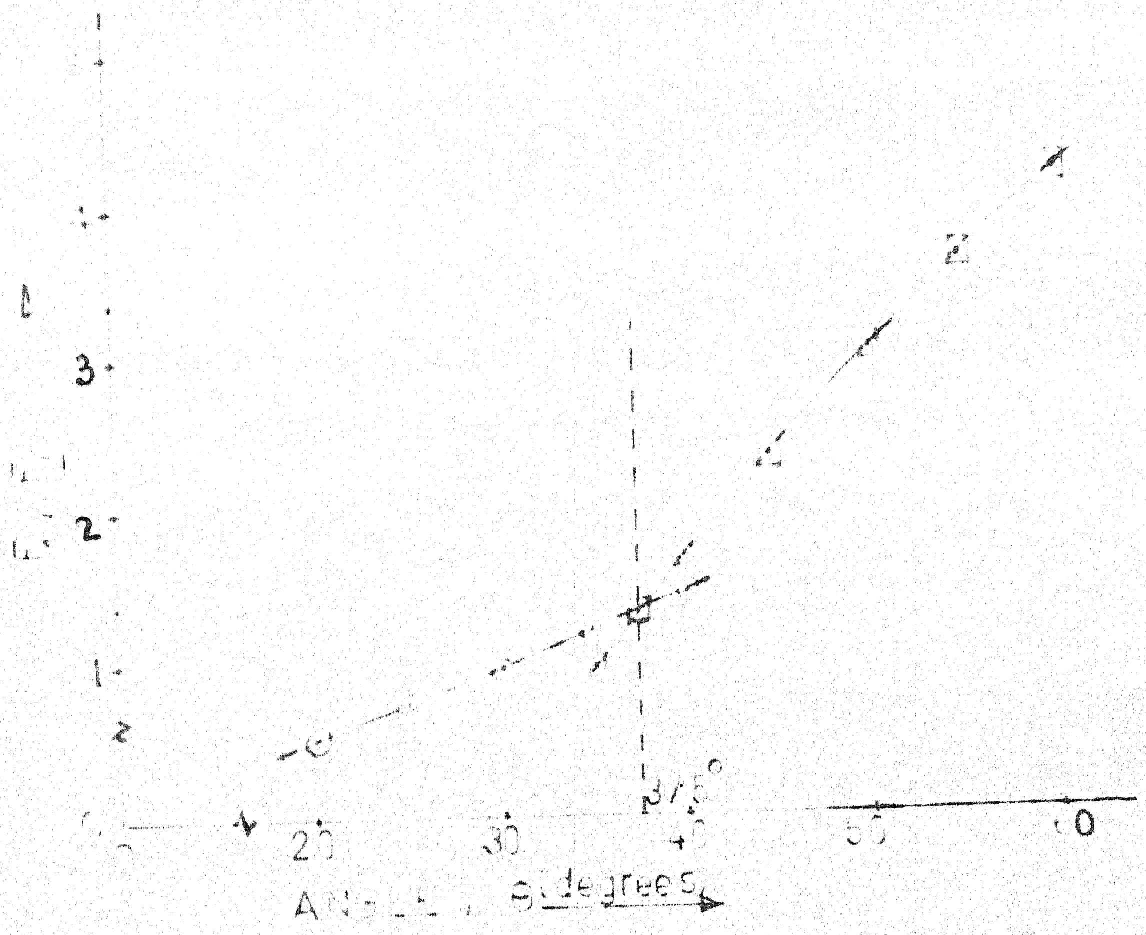

3
2
1
0
20
30
40
50
60
37.5°
ANGLE θ degrees

fig:14

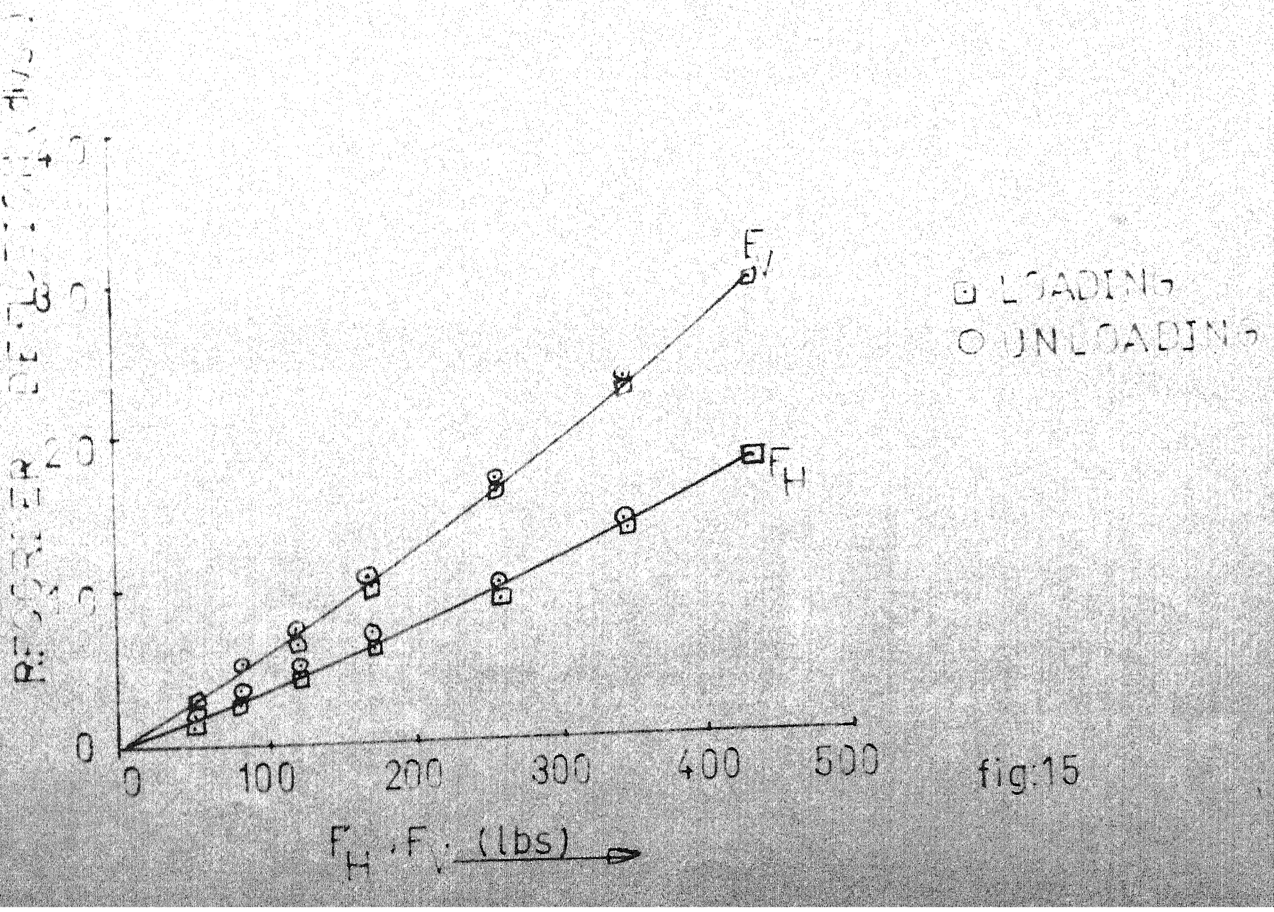
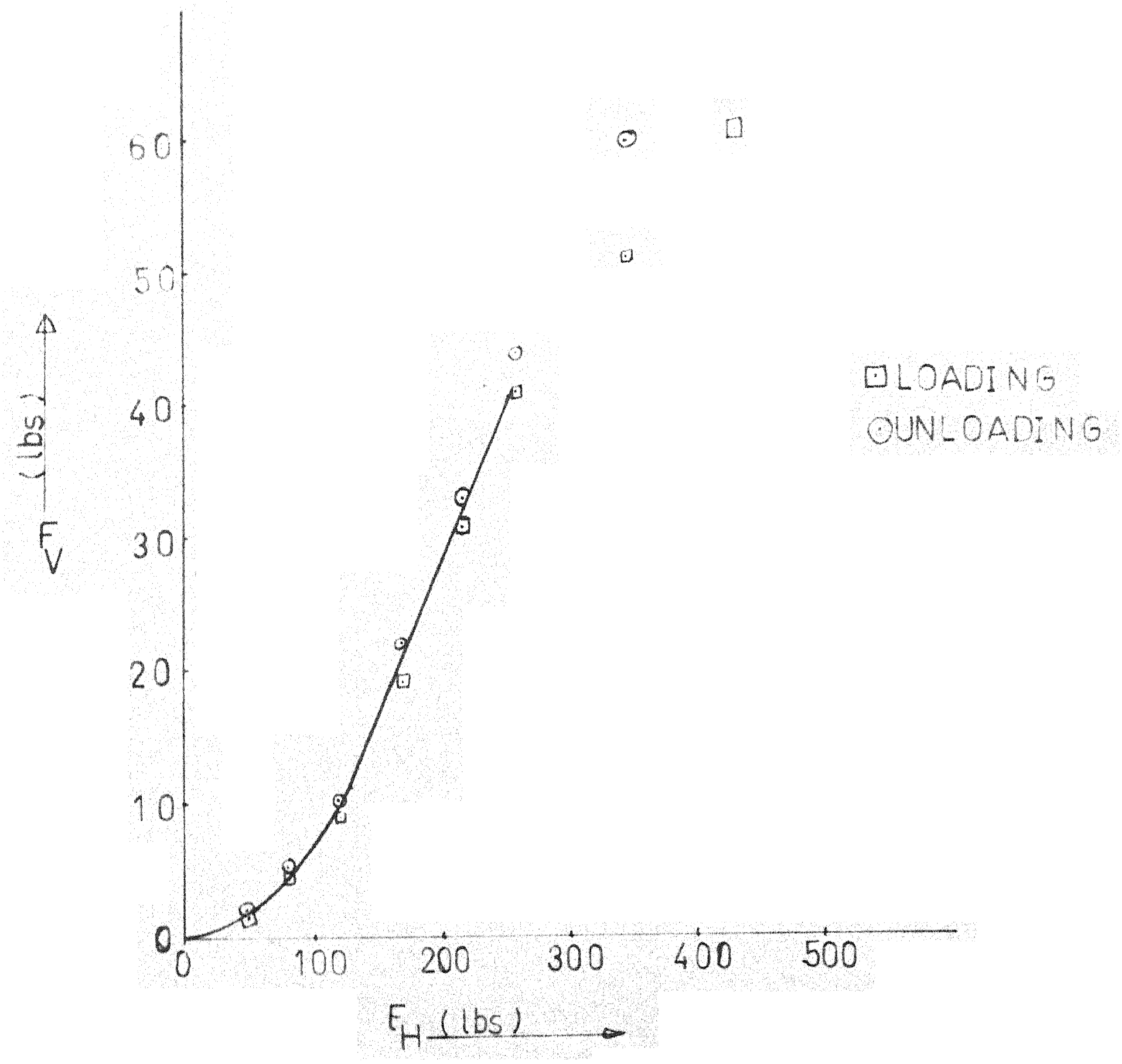

RECORDER DEFLECTION
4.0
3.0
2.0
1.0
0
0
100
200
300
400
500
F_V
F_H
LOADING
UNLOADING
F_H, F_V (lbs)

fig:15



60
50
40
30
20
10
0
F_V (lbs)
LOADING
UNLOADING
0
100
200
300
400
500
F_H (lbs)

fig. 16

Work material Lead
Edge radius 0.025 inch
Cutting speed 240 mm/min

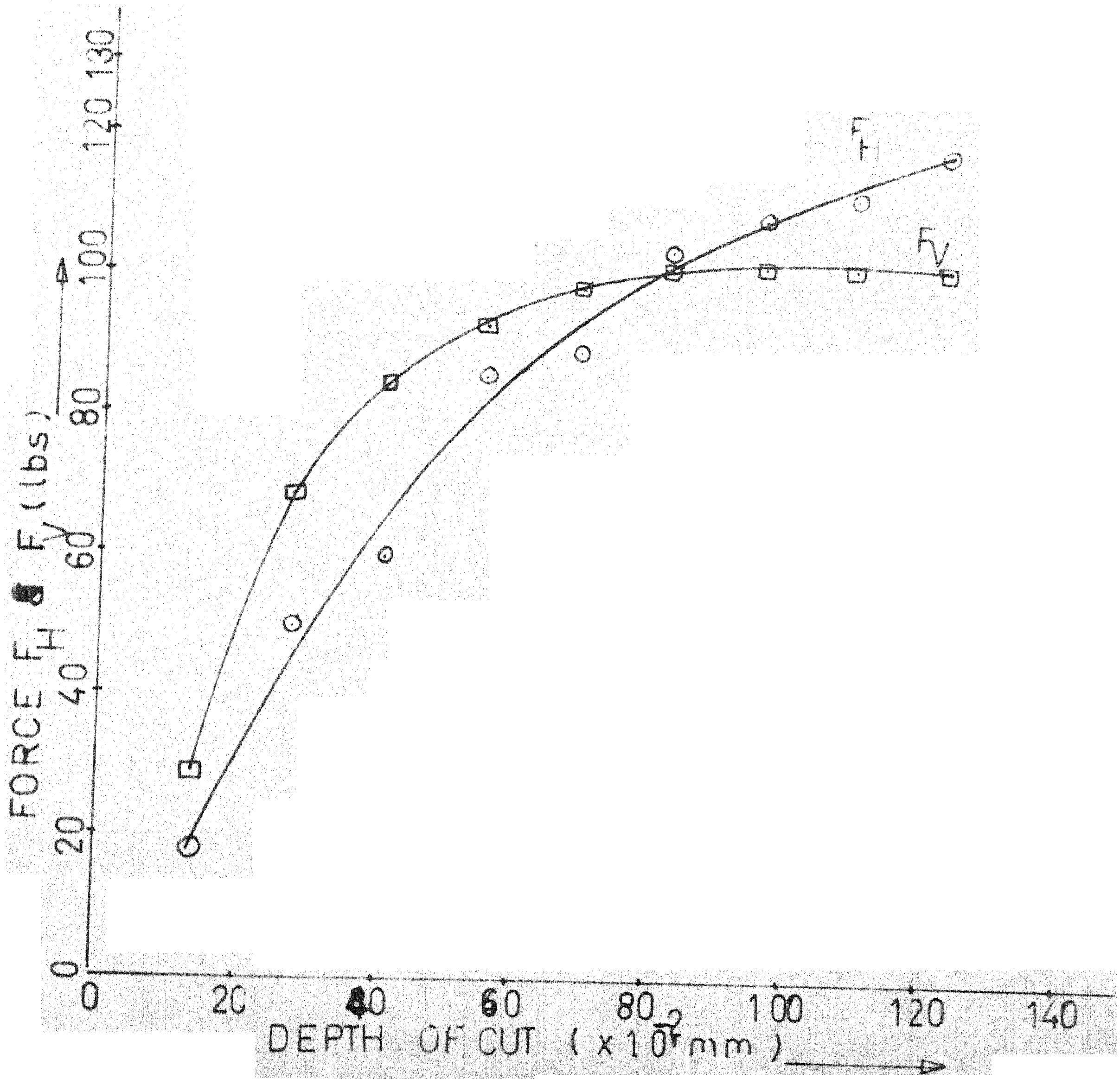


fig: 17

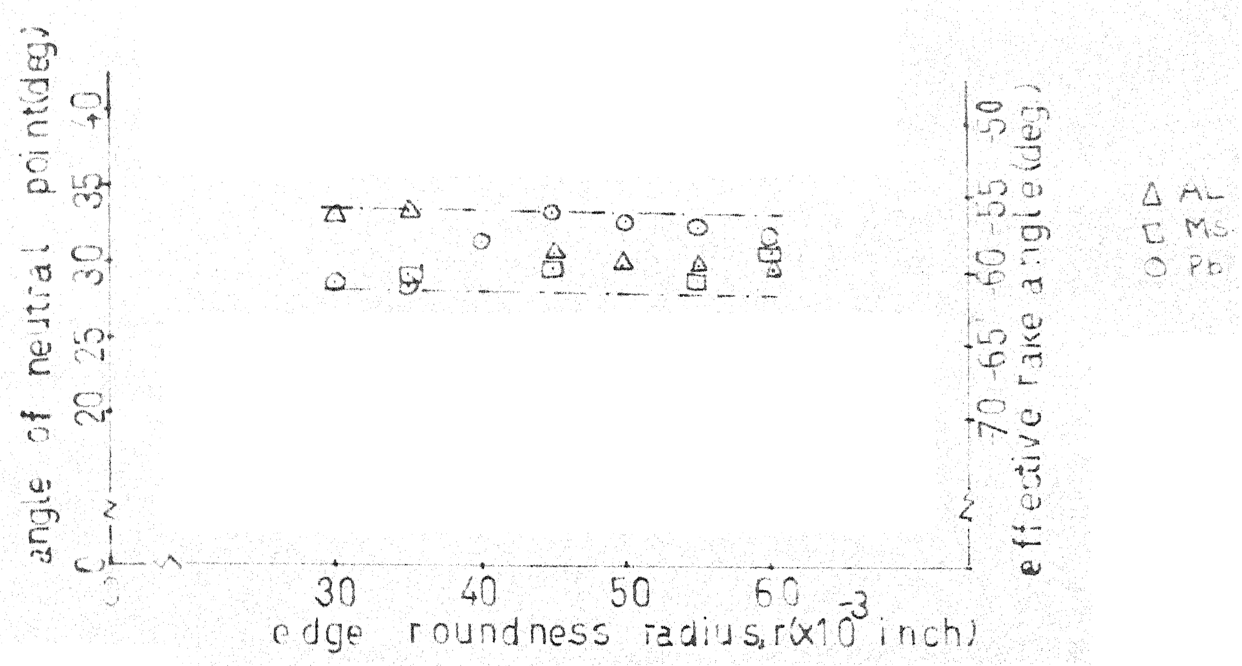

angle of neutral point(deg)
0
20
25
30
35
40
effective rake angle(deg)
70
65
60
55
50
30
40
50
60
edge roundness radius, r(x10⁻³ inch)
Δ AL
□ Ms.
○ Pb

fig: 18

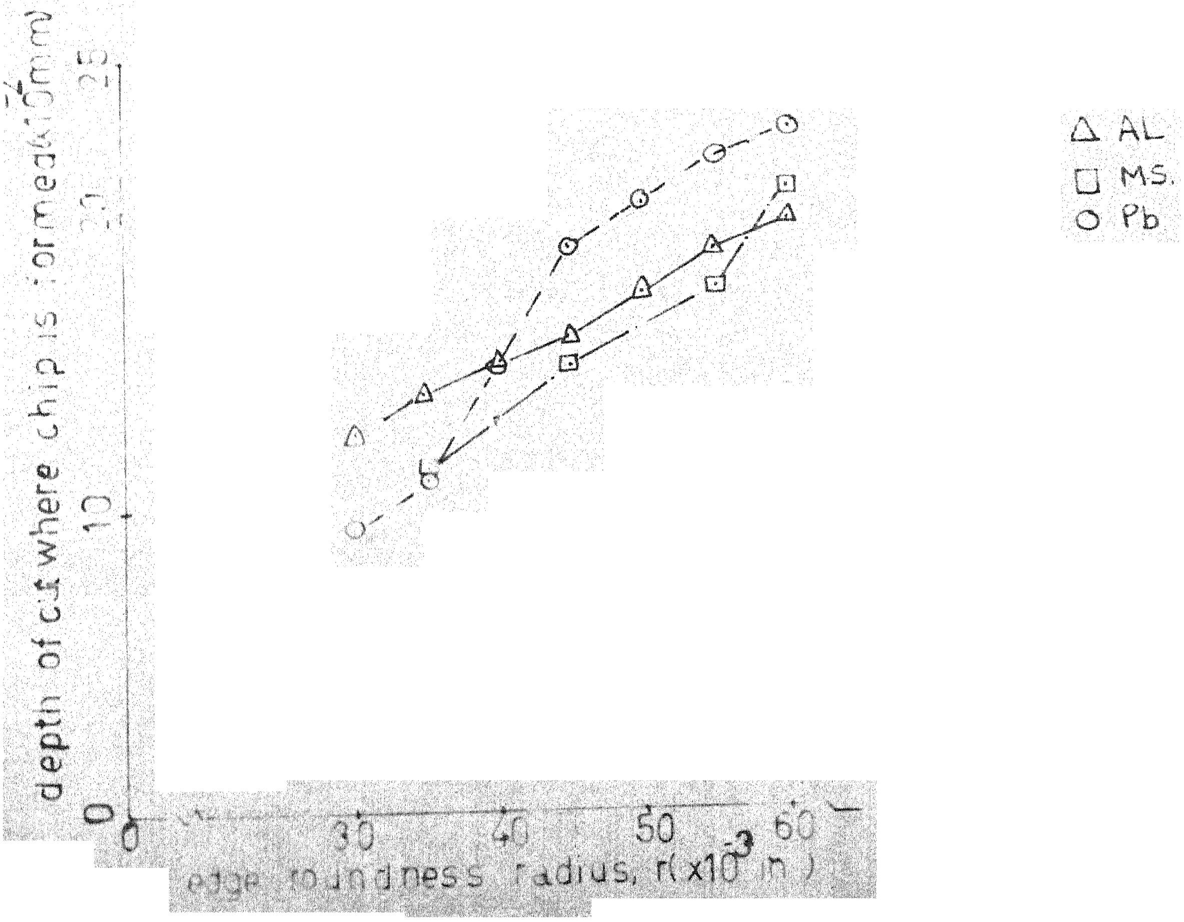

depth of cut where chip is formed
0
10
20
25
0
30
40
50
60
edge roundness radius, r(x10⁻³ in)
Δ AL
□ Ms.
○ Pb

fig 19

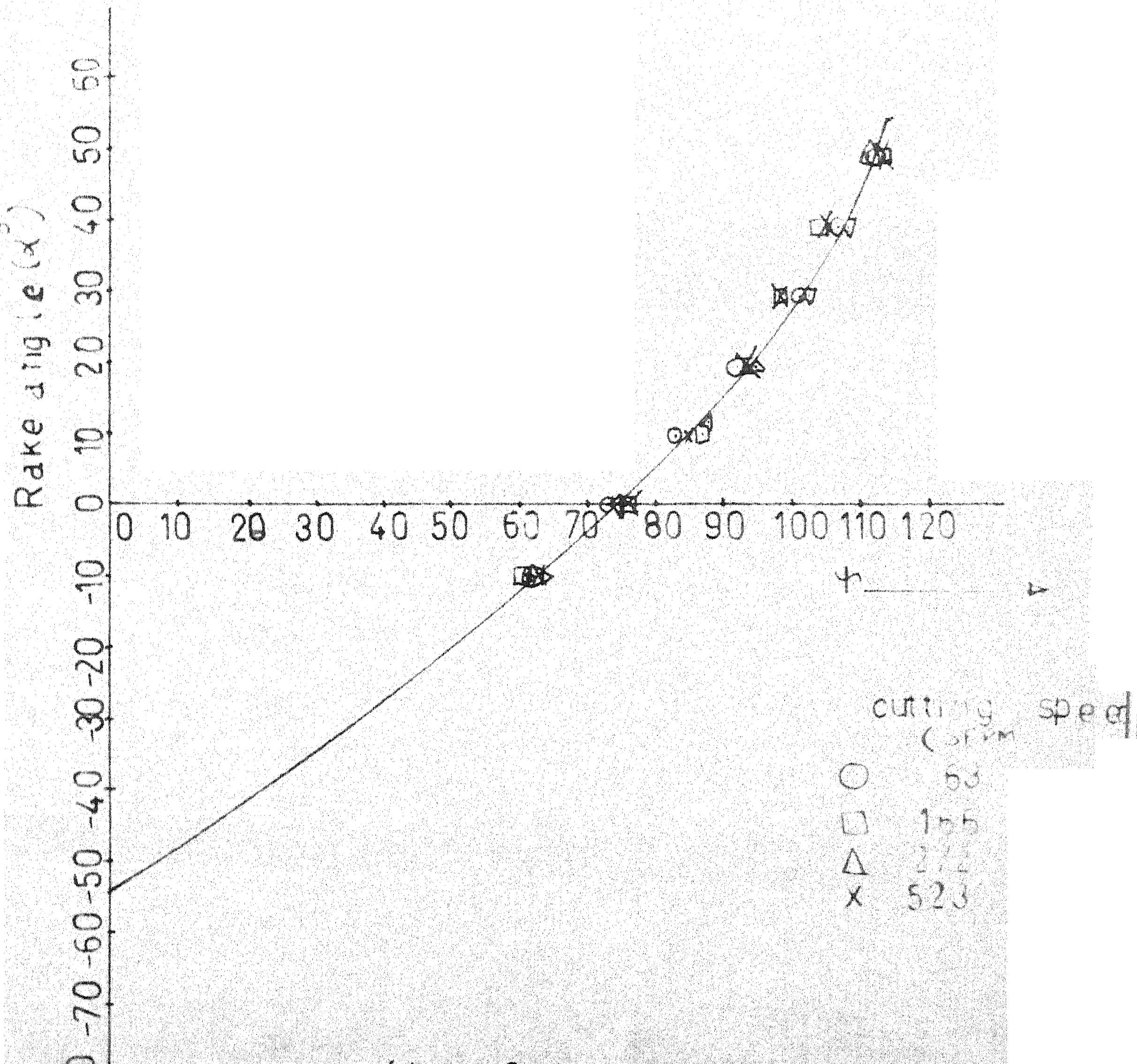
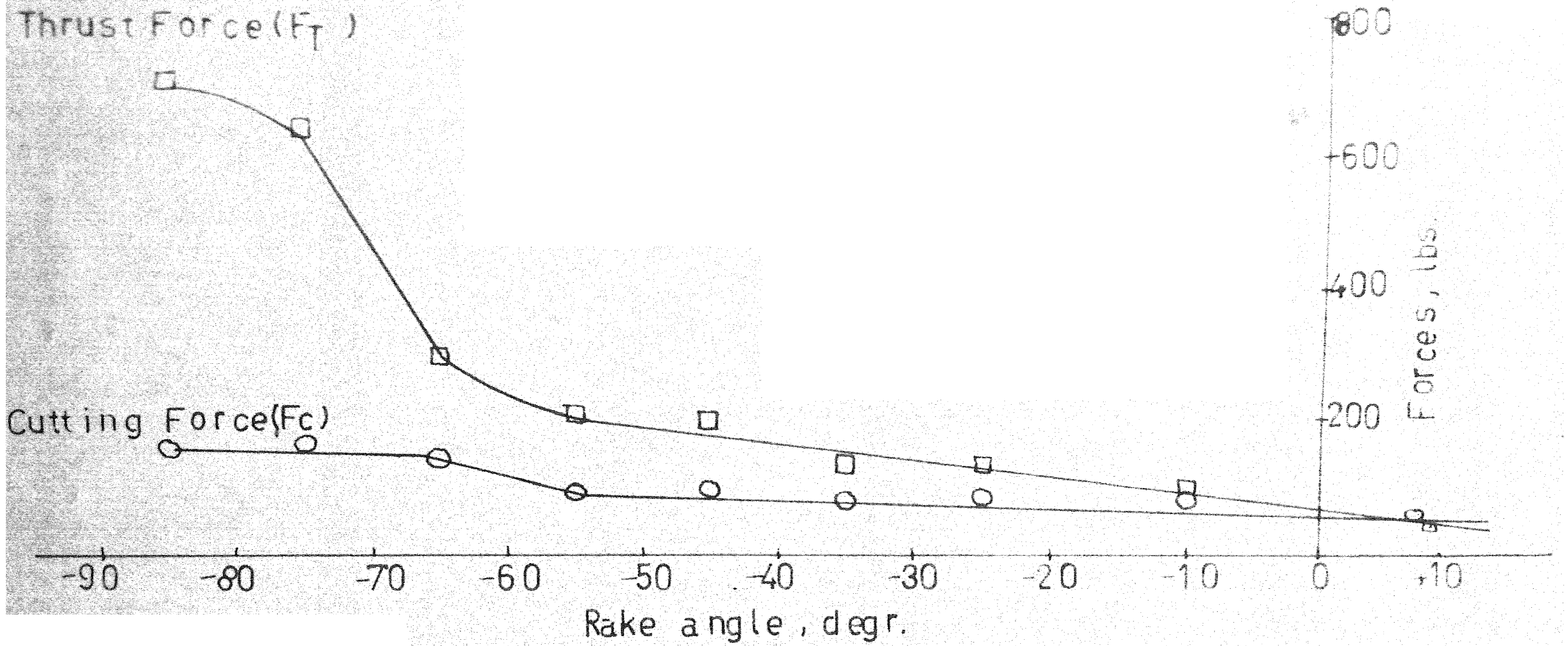

Rake angle (α°)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
0 10 20 30 40 50 60 70 80 90 100 110 120
ψ
cutting speed
523

fig: 20



Thrust Force(F_T)
Cutting Force(F_c)
800
600
400
200
Forces, lbs.
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
+10
Rake angle, degr.

fig : 21

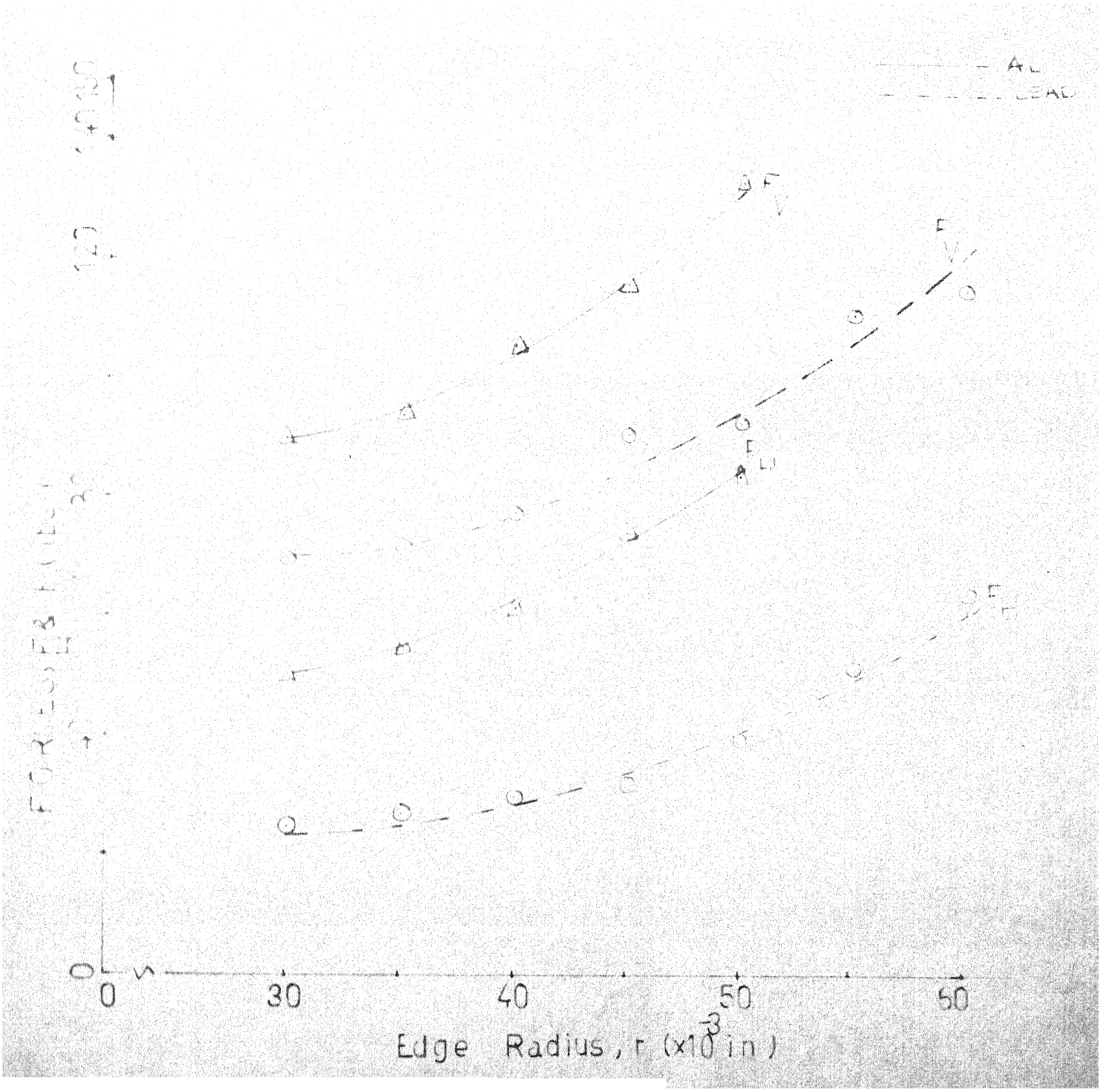


fig: 22

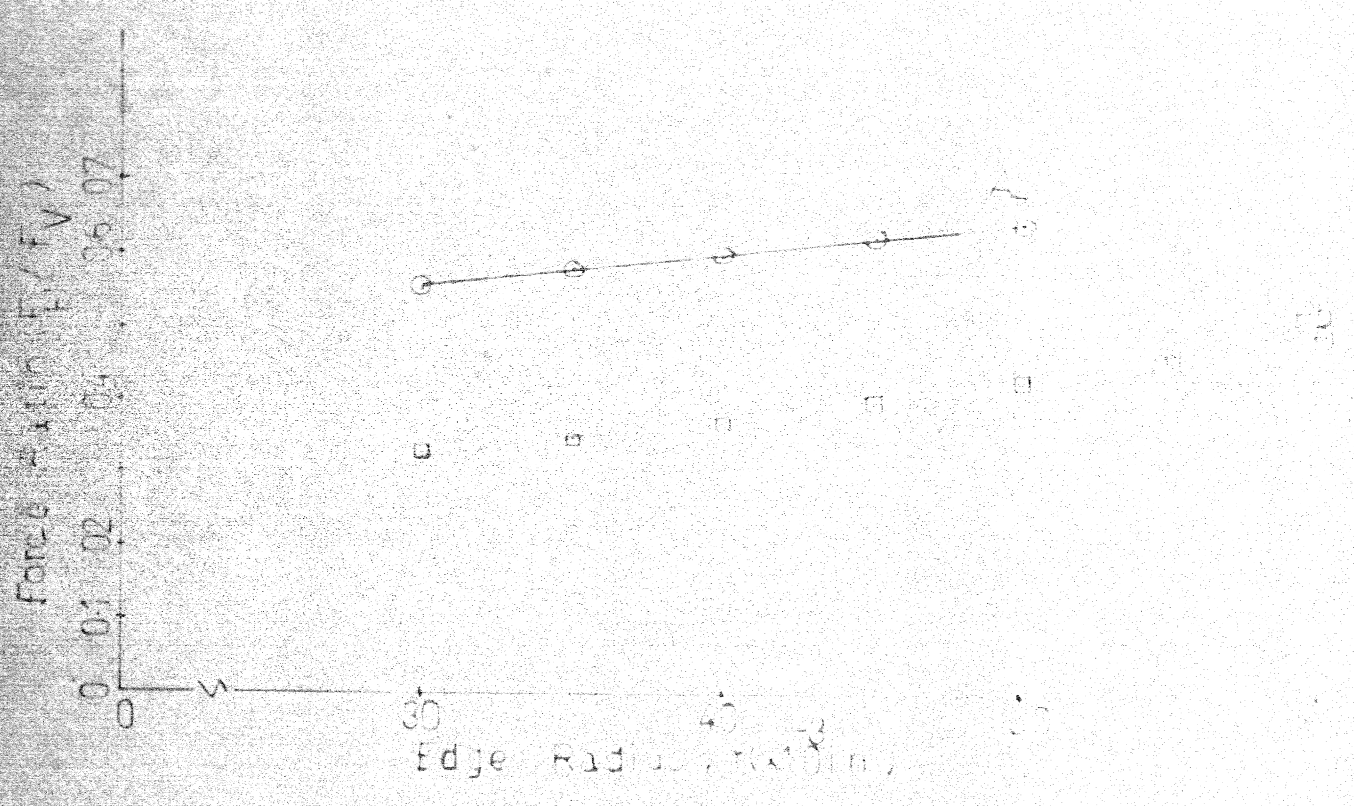


Fig 28

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